CIVIL ENGINEERING
June 1971

Superstructure for 1,350-ft World Trade Center

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The Center has been named winner of ASCE's Outstanding Civil Engineering Achievement Award for 1971. The project is rich in structural innovation, as befits the world's two tallest buildings. Wind loads are taken entirely by the exterior steel box columns and the deep steel-plate spandrels that link them. Both floor and exterior wall structure were prefabricated to expedite erection. Also speeding steel erection are 50-ton tower cranes which can be jumped three floors in two hours. Viscoelastic dampers, 10,000 per tower, were installed to help control wind-induced sway.

In December 1970 the first tenants moved into the North Tower Building of the World Trade Center in New York City.

The project will include two 110-story towers (at 1,350 ft the world's tallest) and four low-rise plaza buildings rising beside a five-acre park-like open plaza (see photo). Completion of the $650 million Trade Center is scheduled for late 1973. The project was undertaken by the Port of New York Authority (PONYA) in accordance with legislation enacted by the states of New York and New Jersey.

Each tower contains 4.8 million gross sq ft of floor area, with 116 framed floors between base plates and roof. Given the 110-story height of the towers above plaza level and the need to provide a sense of security to occupants looking out of windows, architects Minoru Yamasaki and Associates selected a 3 ft 4 in. horizontal module for the exterior wall columns. This results in windows 19 in. wide by 78 in. high, with sills 14 in. above the finished floor; these narrow windows create a sense of security and thus minimize the problem of fear of heights (acrophobia).

Each floor was fixed at 207 ft 2 in. square, with corners chamfered about 7 ft. Tenant areas are 60 ft wide and 35 ft wide between exterior columns and core. Floor to floor heights were set at 12 ft with finished ceilings 8 ft 7½ in. in tenant areas. Tenant areas were designed for 100 psf loads, including finish and partition allowance.

In designing the twin towers, the Port Authority staff and consultants faced two key problems that have long plagued conventional skyscraper design: high structural cost and the large amount of space consumed by elevator shafts.

Elevators

The towers are so tall that to employ the conventional elevator layout would have consumed an inordinate amount of floor space. The imaginative solution developed here is "sky lobbies" at the 44th and 78th floors in each tower (see Fig. 1). In effect each tower thus becomes three buildings, one on top of another. No regular passenger elevator runs all the way to the top. A visitor destined for the 60th floor takes an express shuttle elevator to the sky lobby on the 44th floor, where he changes to a local bound for the 60th. Similarly, a person going to the 90th floor would take a nonstop express to the 78th floor sky lobby, and change there for a local to the 90th floor.

The overall vertical transportation system in each tower calls for 23 express cars, each holding 55 passengers, operating at speeds of 1,600 fpm. In addition, each tower contains 72 local elevators, plus four freight elevators and 16 escalators. Escalators are used to provide transportation between sky lobby floors and floors immediately below and above.

These systems will lift some 22,000 people in each tower to work every morning. To speed operation by encouraging people to move to the back of the express elevator, exit doors are placed on the opposite side of the car from the entrance doors. Studies showed that people tend to slow operation by not moving to the back of the car.

Structural concept

In a building 1,350 ft high, the conventional solution for handling wind load—diagonal braces or shear walls in the central core—was not practical. Design wind shear is 12,500 kips, and wind-moment 9.5 million ft-kips. The

Lester Feld joined the Port of New York Authority's World Trade Center Planning & Construction Division in 1962 as a planning engineer and was promoted to project administrator in 1968. He is responsible for coordinating the structural steel and foundation designs, contracts and specifications, and evaluates construction methods, costs, and staging. Before joining the PONYA staff, he was a structural engineer with Foster Wheeler Corporation. From 1942-45, he was with the Maps and Surveys Division of the Tennessee Valley Authority.

PLAINTIFF'S EXHIBIT PX-630

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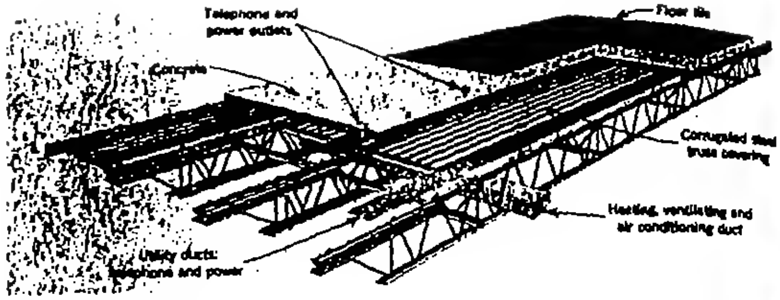


Fig. 2. Floor system.

longest possible resisting moment-arm was required, so the 207-ft-long exterior walls were mobilized for this purpose. The 240 exterior wall columns, spaced at 3-ft 4-in. centers, were tied by 52-in.-deep steel plate spandrels at each floor to form a Vierendeel truss.

All wind forces are taken by these trusses in the plane of each wall. The walls are rigidly connected to each other at the corners to form a tube 207 ft square. This tube has great torsional resistance, and in turn, each of the 240 box columns also has excellent resistance to torsion.

Loads are distributed among the columns by the 4-in.-thick, 3,000 psi lightweight concrete floor slabs, and by the trusses which support the floor.

Floor system

Floor structure was fabricated by Laclede Steel Co. Trusses are paired (7 in. e-c) and the pairs are spaced two window-modules apart—6 ft 8 in. The trusses span between the core and the exterior wall (35 to 60 ft). Each truss consists of pairs of angles at both top and bottom chords, with the pairs spaced 29 in. apart by sawtooth webs of bar stock (see Fig. 2). Note that the top "knuckle" of the web projects three in. above the top chord: these knuckles are utilized as shear connectors to make trusses and concrete slab work compositely. Bridging trusses placed at 90 deg from the major trusses, and spaced at 13 ft 4 in. centers, serve as lateral bracing. At the building corners, moment connections are used to achieve two-way truss action.

Steel deck is corrugated (not cellular) 1½ in. deep, of 22 gage galvanized steel. In Fig. 1 the dark decking units are power/telephone cells, centered 20 in. from each pair of trusses. The decking and P/T cells, by

About the World Trade Center

The World Trade Center includes the world's two tallest buildings, each 110 stories and 1,350 ft high (100 ft higher than the previous record holder, the Empire State Building). Together with several lower office buildings the $650 million project will include some 9 million sq ft of office space.

The World Trade Center was conceived as a magnet to maintain and build the city and region as the continent's major port (the Trade Center's owner is the Port of New York Authority). It will bring together for the first time businesses and government agencies in the processing and marketing of world trade.

The soils and foundations work for the Center were described in "Slurry-Trench Construction for Basement Wall of World Trade Center," April 1969 issue, which won for author Martin Kapp ASCE's Greensfelder Award as this magazine's outstanding construction article of that year.

The logistics of planning and coordinating construction, involving 200 prime contractors and thousands of workers, led to a CPM scheduling effort which won for the Port Authority's Ray Monti the Construction Man of the Year Award of *Engineering News-Record* magazine for 1971.

The first tenants moved into the Center in December 1970, and the project is expected to be completed in 1973.

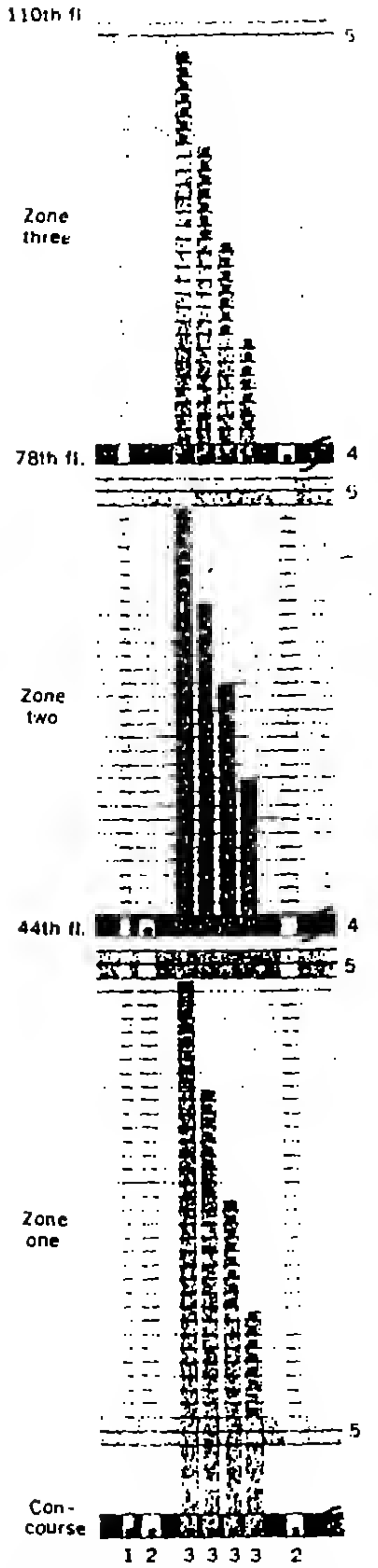


Fig. 1. "Sky lobby" elevator concept significantly reduces building volume devoted to elevator shafts.

KEY
1 Express to Top
2 Express to Skylobbies
3 Local Service
4 Skylobby Floors
5 Mechanical Floors
Escalators
• Floor Stops

continued

Granco Steel Products Co., serve as a form for pouring the concrete floor and as a working platform; the decking has no structural function. It was found less costly in this very tall building, with high wind shears, to use this approach.

Across the Hudson River from the site, loose decking and floor trusses are assembled into modular floor panels (as shown in Fig. 2) by Karl Koch Erecting Co. Floor panels range in size from 13.33 x 35 ft, to 20 x 60 ft, and weighing 10 psf. These units are barged across the Hudson to the site, and hoisted into place using slings placed through the knuckles. Each typical floor required 32 panels.

Damping units

Among the innovations at the World Trade Center are "viscoelastic damping units," the heart of which is a steel-plastic sandwich. In each tower some 10,000 units, 100 per floor placed in the 7th through 107 floor, are employed to decrease perceived wind-induced sway (see Fig. 3). These dampers or "shock absorbers" dissipate sway energy in the form of heat of friction. They are bolted between the exterior wall (but not core) columns and the ends of the bottom chords of each floor truss. The damping units were manufactured by the 3M Company from their own viscoelastic material (polyacrylic), which is epoxy-bonded to machined steel fabricated by Levinson Steel Co.

Exterior columns—9th through 107th floors

To speed erection and thus minimize cost, exterior-column spandrel units were prefabricated in panels three bays (10 ft) wide and, generally, three stories (36 ft) high (see photo).

The contract for these 5,668 panels with total weight of 55,800 tons was awarded to Pacific Car & Foundry Co. The steel was fabricated into panels at its Seattle, Wa., plant and then shipped by rail to a storage yard across the Hudson River from the site.

Panels vary in weight from 6 tons at the 107th floor to 22 tons at the 9th floor. To keep within the architectural envelope specified (constant spandrel depth of 52 in., and column dimensions of 14 x 13½ in.), steel plate thickness and yield strength was varied.

PCF did a remarkable job of fabricating and delivering the panels on time and within the specified length of 36 ft ± 1/32 in. Careful quality control, machined column end-plates, and go-no-go jigs were used for this purpose. The precision achieved is more reminiscent of craftsmen than of fabricators.

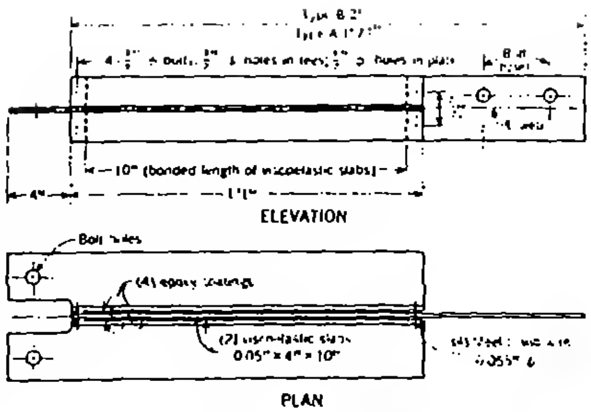


Fig. 3. Sway is dampened by 10,000 of these assemblies in each tower. They are bolted to the lower chord of the floor truss, and to the exterior (not interior) columns.

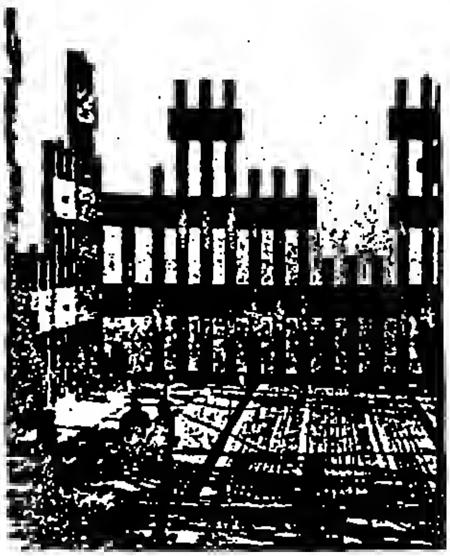
Because of the large number of panels, a conveyor-line automotive type assembly line, perhaps unique for structural steel, was developed. First the "bed plate", consisting of spandrels and inside column plates, was welded into one piece. At another station the three additional plates for each box column were welded into U-shaped partial assemblies. Finally the U's were welded to the bed plate.

The 5,668 exterior wall panels required preparation of 39,700 shop drawings. Prepared manually this task would have required 10 man-years: PFC wrote a computer program and completed the task in six months.

For the exterior steel panels, shop fabrication was by welding, and field connections were bolted except for splices at mechanical equipment floors. The prefab exterior panels were planned so only one-third of the panels are spliced at any one tier. All exterior column-splices are bolted using handholes at inside column plate for access to butt-plate bolts. Spandrel splices are also bolted, and occur at points of contraflexure.

Exterior thermal insulation

Based on Battelle Memorial Institute studies on heat transfer through exterior walls, performance specifications were developed for the aluminum curtain walls and fireproofing of the tower buildings. Maximum differential temperature between the inside and outside faces of an exterior column was set at 20 deg F. This was done by carefully selecting the thermal insulation of the exterior



Wall panels and floor panels in place. Note that only one-third of the wall panels are spliced at any one floor. Handholes for bolting column endplate to endplate are visible near men at rear. Spandrel connections are also bolted. Dark colored strip fills gap between adjacent floor panels.

columns (see Fig. 4). Fireproofing on the outside and side faces of the exterior columns has a lower coefficient of thermal conductivity than the interior material. Thus the exterior column steel maintains a temperature near that of the building interior. The interior material is vermiculite plaster, and doubles as wall finish. The outside fireproofing is Cafco Type D. This is believed to be the first use of a non-asbestos sprayed fireproofing on a major building. The Cafco fibers are ceramic.

Exterior columns below the 9th floor

Above the lobby, the column module changes from 10 ft to 3 ft 4 in. A total of 152 of the resulting "tree"

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modules (see photo), each 56 ft high and weighing up to 52 tons, were fabricated by Pittsburgh-Des Moines Steel Co. These trees carry loads up to 4,600 kips each. Some 108 plates are used in each tree with plate thicknesses up to 6 in. and yield strengths to 70 ksi. 270,000 lb of weld wire was used by PDM on this 6,800-ton contract.

Below the trees, even thicker steel was employed. In its contract, Atlas Machine & Iron Works made the first major U.S. structural application of electroslag welding. Some 200,000 lb of weld metal was applied in welding plates up to 7 in. thick to form the 27 x 32-in. box columns, spandrels and X-bracing in this 13,600-ton contract.

Core and plaza framing

Mosher Steel Co. fabricated 13,000 tons of box columns and built-up beams below the 9th floor. The heaviest box columns, with double webs 22 x 52 in. and weighing 3,150 lb per ft, occur at the corners of the core. All core columns were fabricated in three-story lifts.

Stanray Pacific Corp. fabricated 31,100 tons of box columns and built-up beams above the 9th floor. To position and align box column plates, this fabricator used an interior expandable mandrel and exterior clamps to achieve dimensional tolerance.

All rolled columns and beams, including cover-plated sections throughout both Towers were fabricated by Montague-Betts Co. Inc. The 25,900 tons of steel in this contract included the heavy braced horizontal trusses at the cantilever balcony on the 2nd floor. M-B was also awarded supplemental contracts for the exterior wall steel above the 107th floor and the weldments for supporting future T.V. masts.

Base plates and grillages were fabricated by Dreier Structural Steel Co. Inc.

The temporary truck platforms required around each Tower for erection of Tower steel made this package "critical" on all CPM runs. Lead time between release of design drawings and erection dates averaged only 3 to 5 months. The Levinson Steel Company fabricated 12,000 tons of heavy 14 WF sections with shear heads to receive the 10- and 11-in. flat concrete slabs in the subgrade area columns spaced on a 30 x 30-ft grid.

Shop drawings

The Authority awarded Nassau Bridge Detailers (NBD) of Jericho, N.Y., a prime contract on detailing for Mosher and Montague-Betts. NBD was also a subcontractor to

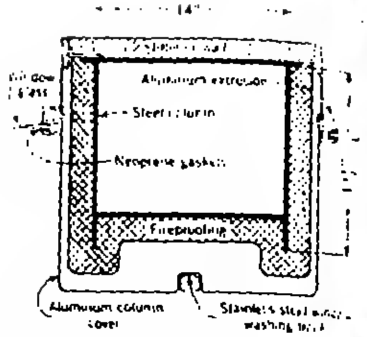


Fig. 4. Cross-section of exterior column, with fireproofing, column cover, and windows.

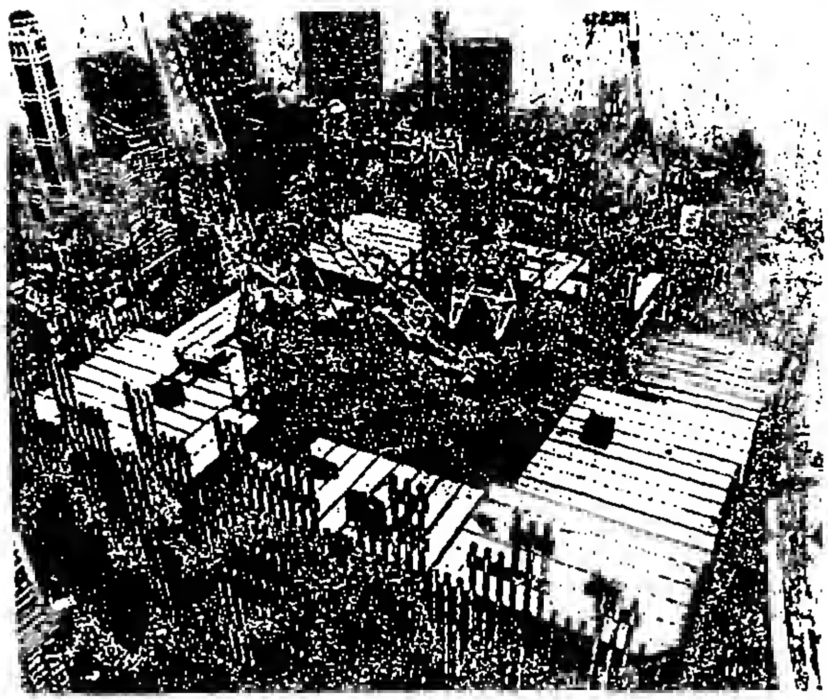
Dreier, Atlas Machine & Iron Works, and Karl Koch Erecting Co. Inc. and matched connections at all contract match-lines. Dovell Engineering, Inc. of Los Angeles was the subcontractor to Stanray Pacific and provided all details in the core from 9th through 106th floors to Stanray and Montague-Betts.

Steel erection: Kangaroo crane

Most apparent innovation by Karl Koch Erection Co. is "Kangaroo" tower cranes, so named because they can be jumped quickly and came from Australia. Whereas with the traditional guy derricks it may take two days to jump three stories (36 ft), the Kangaroo crane can do it in two hours. The jump is made in three, 12-ft increments. The procedure is outlined in Fig. 5.

Each crane rests on a braced steel tower 120 ft high, with one-third of this height projecting above the building core, to which the tower is tied. Thus three floors of steel can be erected before a new jump is required.

The cranes, four to a World Trade Center tower, work quickly, erecting three floors every 10 working days. The eight cranes erected a total of 1,125 tons per day during peak operations. Each crane has a 50-ton capacity at 60-ft radius. Unlike guy



Four tower cranes are mounted in each tower, with the tower for each in an elevator shaft in a corner of the building's core. The cranes can erect three floors of columns and floors (including 240 exterior column spandrel panels and 246 floor panels) in 10 working days. Equally responsible for this speed is the efficient procedure for having the correct panels, column and floor, ready to be hoisted at the right time and location.

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derricks, its rotation is not impeded by guys. These Favco STD 2700 cranes are manufactured by Favelle Industries Pty. Ltd.

Steel procurement

More than 180,000 tons of steel are being placed in the twin towers. After evaluating bids received in August, 1966 for a single large contract for detailing, furnishing, fabricating and delivering this tremendous quantity of steel, the Port Authority decided to break the job into several contracts, with the scope of the work suited to the fabricating equipment available in many of the large fabricating shops throughout the country. This multi-source approach reduced steel cost, but also necessitated separating the 400 structural drawings and 3,800 pages of drawing books into 13 steel contract packages. With the aid of Tishman Realty and Construction Co. Inc. the Port Authority's Planning and Construction staff negotiated and awarded 13 fabricating contracts, one erection contract and one detailing contract, all within nine months.

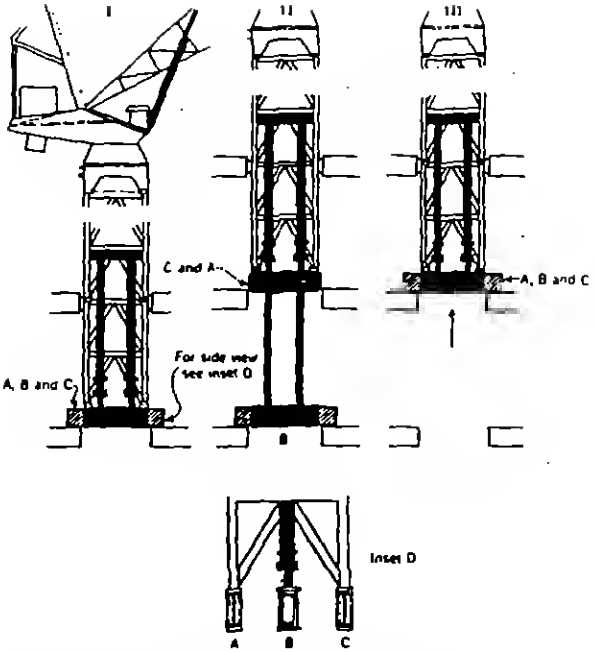

Fig. 5. Method by which Kangaroo Crane climbs. In stage I, arms (in black) of beam B are extended at both ends and used to support the 120-ton crane on building frame. In stage II, crane and tower are lifted by the two hydraulic rams. In stage III, extendable (internal) sections of beams A and C are extended to support the crane. Extendable ends of beam B are retracted, and the hydraulic cylinders lift this beam to the level of A and C.

Design for wind

The character of wind gusts, directions and velocities over the existing environment at the southern end of Manhattan was obtained from several sources, and computer-analyzed by structural consultant Skilling, Helle, Christiansen, Robertson (SHCR). The velocity profiles obtained were duplicated in a wind tunnel at Colorado State University. Varied percentages of structural damping were simulated by spring-mounted tower models controlled by electro-magnetic action. A 1:500 scale model of the twin towers including lowrise plaza buildings and surrounding buildings was rotated through 360 deg in 5-deg increments, and readings were taken at some 250 pressure taps per tower. A study of the effect on wind of varying the distances between the two towers provided guidelines for placing the towers relative to each other. The Colorado tests were confirmed by other tests conducted at the National Physical Laboratory in Teddington, England. The design criterion was a 140-mph (100-year) hurricane wind. This is equivalent to a static wind load of 55 psf for the upper 100 ft and 45 psf over the remaining portion of the tower.

Horizontal acceleration

In order to determine acceptable levels of horizontal acceleration, physiological tests were conducted at the Oregon Research Institute. These tests, aimed at determining human sensitivity to such acceleration, took place in a moving room mounted on a track with horizontal movements accelerated to simulate the oscillatory motion of a tower.

Later, the same physiologist conducted tests in the ventilation building of PONYA's Lincoln Tunnel. In this second series, the test "room" was suspended from rods and was moved through various amplitudes up to 12 in. each side of the vertical. The room was prevented from swaying laterally by means of horizontally mounted bicycle tires. Accelerometers were attached to the underside of the room, with an oscilloscope recording accelerations. The data collected indicated that the threshold of human awareness to horizontal accelerations is in the range of 6 to 15 milli G's (milli $G = .001G$, with $G = 32.2$ ft^2, that is, the acceleration of gravity). The subject's position (sitting, standing, high heels, etc.) and occupational activity level were found to greatly influence sensitivity. Design criterion adopted is 10 milli G's at the top occupied floor, not to exceed a frequency rate of 12 times a year. The building has a period of vibration of approximately 10 seconds and a 2½-percent damping ratio. To achieve this level of comfort, the amplitude of static plus dynamic deflection was limited to a maximum of ¾ in. per story with 140-mph winds, in part by use of the damping units discussed earlier.

Credits

In addition to organizations mentioned above, the following persons and organizations were among those playing key roles: For the owner, Guy F. Tozzoli, director, World Trade Department; and Malcolm P. Levy, chief of Planning and Construction Division, World Trade Center. The architects were Minoru Yamasaki & Associates, and Emery Roth & Sons. Foundations and utilities were designed by PONYA's engineering department, Martin S. Kapp, chief engineer. Structural engineers were Skilling, Helle, Christiansen, Robertson. Mechanical Engineers were Jaros, Baum & Bolles. Electrical Engineers were Joseph R. Loring & Associates. The General Contractor Agent was Tishman Realty & Construction Co., Inc. James R. Endler, vice president in charge.